(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
30 May 2002 (30.05.2002)

PCT

(10) International Publication Number
WO 02/42713 A2

(51) International Patent Classification[7]: G01B 7/00

(21) International Application Number: PCT/EP01/13698

(22) International Filing Date: 21 November 2001 (21.11.2001)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
0028343.2 21 November 2000 (21.11.2000) GB

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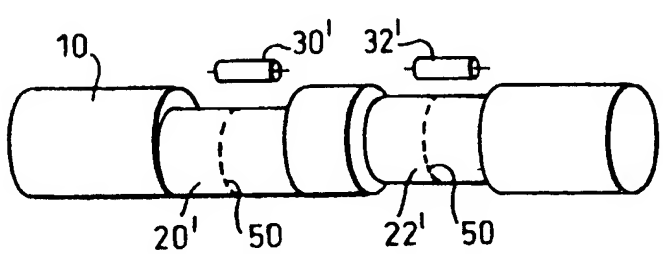
(81) Designated States *(national)*: AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ, NO, NZ, PH, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TR, TT, TZ, UA, UG, US, UZ, VN, YU, ZA, ZW.

(84) Designated States *(regional)*: ARIPO patent (GH, GM, KE, LS, MW, MZ, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE, TR), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Published:
— *without international search report and to be republished upon receipt of that report*

For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

(54) Title: ANGLE MEASUREMENT BY MAGNETIC TRANSDUCER



(57) Abstract: A magnetic transducer for measuring the angle about an axis (A-A) of a part such as a shaft (10) is constructed to emanate a magnetic field which is detectable by a fixed sensor (30) to produce a signal which is dependent on the angle. The construction may include a transducer element (20: 70) mounted eccentrically with respect to the axis (A-A) or a magnetically-conductive element (92) having a surface (94) whose radius is a function of angle. Alternatively a part of circular cross-section is given a radial depth (122) of permanent magnetisation which is a function of angle or is provided with a magnetised zone (142') of different magnetic property to the remainder and having a radial depth which is a function of angle. Such a zone may be a case-hardened zone of a steel part. Transducer regions (20, 22) arranged at 90° can be used in resolving ambiguities in the measurement. The transducer region or a magnetically conductive part (112, 114) thereof may provide a cyclic variation of the emanated magnetic field within one revolution of 360°.

WO 02/42713 A2

Title: Angle Measurement By Magnetic Transducer

FIELD OF THE INVENTION

This invention relates to an angle-sensing transducer and to a transducer element therefor.

More particularly the invention is concerned with a transducer for the measurement of the angle of a rotatable part with respect to a datum position over a continuum of angular range. Such measurement is contrasted with measurement afforded by counting increments of angular displacement marked by a sequence of detectable items disposed at discrete angular values.

Still more particularly the invention is concerned with a transducer based on magnetic technology, that is a magnetic transducer element and a sensor arrangement which is responsive to a magnetic field emanated by the transducer element. Such magnetic transducers have the advantage of enabling detection of the field without contact between the element and the sensor and in circumstances where another part may be interposed between the element and the sensor provided the other part is magnetically permeable: that is the part does not screen the sensor from the field.

BACKGROUND TO THE INVENTION

Magnetic transducer technology has utility in the measurement of torque and force and has found particular use in the non-contact measurement of torque. Torque may be measured in a continuously rotating shaft or in a shaft or like part subject to a limited range of angular displacement. The present invention has been developed in the context of a limited range of angular

displacement but is not restricted to such circumstances. Furthermore, the invention may be applied in circumstances where measurement of torque is not of interest.

It has already been proposed in connection with torque measurement by means of magnetic transducer technology, to provide means by which rotational speed can be measured together with rotational position if desired. International Patent Application published under the number WO00/58704 describes various measures applicable to a torque sensor to provide a measurement of speed and some of which are also usable for the measurement of angular position. The measures described in WO00/58704 involve the provision of discrete elements, for example structural or magnetic, angularly spaced around a shaft that is rotatable about a longitudinal axis. The elements provide a magnetic field having an amplitude or waveform that is periodic with angle about the shaft axis and from which speed or angle information is derived. The angular resolution is restricted to the number of discrete angular points at which suitable elements are incorporated.

WO00/58704 also describes various magnetic sensing technologies with which torque, speed and angle measurement can be implemented. One of these is circumferential (circular) magnetisation of a magnetoelastic host such as described in U.S. Patents 5351555, 5465625 and 5520059 and in published International Patent Applications WO99/21150, WO99/21151 and WO99/56099. The disclosures of WO99/56099 and WO00/58704 are incorporoated herein by reference. Another form of magnetisation disclosed in WO00/58704 is longitudinal magnetisation which is of the form known as circumferential

(tangential)-sensing longitudinal magnetisation. Further information on this form of longitudinal magnetisation is to be found in International Patent Application published under the number WO01/13081 on 22 February 2001, the disclosure of which is incorporated herein by reference.

Yet another form of longitudinal magnetisation is referred to as profile-shift sensing longitudinal magnetisation and is described in International Patent Application published under the number WO01.79801 on 25th October, 2001, the disclosure of which is incorporated herein by reference. Whereas circumferential magnetisation relies on the material of the transducer element exhibiting significant magnetoelasticity, this is not a requirement of the wider range of ferromagnetic materials to which the above forms of longitudinal magnetisation are applicable.

It will be understood that the circumferential and longitudinal magnetisation that have been referred to above is each a stored or permanent magnetisation in the transducer region which enables the region to emanate a detectable magnetic flux for measurement purposes.

Proposals for combined torque and speed measurement for magnetic transducer using a ring-type magnetoelastic transducer element are also described in "A single Transducer for Non-Contact Measurement of Power, Torque and Speed of a Rotary Shaft", I. J. Garshelis, C. R. Conto and W.S. Fiegel, SAE Technical Paper Series No. 950536 published 1995 by the Society of Automotive Engineers, Inc. Reference may also be made to U.S. Patent 5 708 216 (Garshelis). Other proposals for torque transducers using pairs of rings of discrete magnets are disclosed in EP-A-0338559 and JP 1276033.

The prior proposals mentioned above, as far as directed to angular position measurement, disclose the provision of a structural or other detectable element at each of discrete points about the axis of rotation. Not only does greater resolution require a greater angular density of points and a more complex structure but a point counting procedure is also required, more specifically to determine count per unit time. The sensed output is essentially a repetitive waveform whose period in time is that of the discrete points in angle. Angular measurement is not determined from the magnitude of the waveform: cycles of the waveform are counted. There is a need, therefore, to provide a method and apparatus for measurement of the angular position of a shaft or the like by means of sensing a magnetic field whose magnitude is a direct function of angle at least over a range of angles. That is angular measurement can be made over a continuum of angles rather than at discrete points.

There will be described hereinafter methods and apparatus according to the present invention which provides an angle-dependent sensed magnetic field which is a monotonic function over a range of angles, such as up to 180° or even 360° or closely approaching it, with respect to a datum position and which in a preferred form enables a direct measurement to be made of angles over a full 360° even for transducer elements which individually are ambiguous over that full range.

The basis of the invention is applicable to any form of magnetisation of a transducer element, but is of particular advantage applied to a form of magnetisation which generates a quiescent external field at zero torque. This is the case with the two forms of longitudinal magnetisation described in

WO01/13081 and WO01/79801 referred to above where there is an inherent external field that accompanies the magnetisation. Such an external field is detectable by a sensor arrangement to obtain the measure of the field strength. This is not the case for circumferential magnetisation where normally the magnetic field is contained within the transducer region in the absence of torque. For the purposes of the present invention a circumferentially magnetised transducer element or elements can be operated under torque or subject to a pre-torque process to generate a field at zero torque as is described in International Patent Application published under the number WO00/57150. Pre-torquing (magnetising a transducer element while under a predetermined torque) is also applicable to longitudinal magnetisation. It may be used for example to generate a quiescent (zero torque) circumferential field component in the form of longitudinal magnetisation described in Application WO01/13081 in addition to the axially-directed reference component resulting from such magnetisation.

The present invention will be further described below in relation to an embodiment in which the transducer element(s) is prepared with the profile-shift kind of magnetisation described in WO01/79801. More particularly the radial component of the profile shift is measured.

SUMMARY OF THE INVENTION

Aspects and features of this invention for which protection is sought are set forth in the Claims following this description.

In order that the present invention and its practice may be better understood, embodiments of it will now be described with reference to the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 shows a perspective view of a transducer having a single transducer element in a shaft in accordance with one embodiment of this invention;

Fig. 2 is a cross-sectional representation of the transducer of Fig. 1 showing the offset of the transducer element;

Fig. 2a shows the zero angle position of the shaft for the graph of Fig. 3;

Fig. 3 is a graph showing the response of the transducer as a function of shaft angle;

Fig. 4 is a perspective view of a transducer system having two transducer elements in a shaft in accordance with this invention, with respective offsets for overcoming ambiguity in measurement over a 360° range;

Fig. 5 is a cross-sectional representation of the transducer of Fig. 5 showing the offsets of the two transducer elements;

Fig. 6 is a graph showing the respective responses of the transducers of Fig. 6;

Fig. 7 is an explanatory illustration of the means for magnetising a transducer region to exhibit profile-shift longitudinal magnetisation;

Fig. 8 is a graphical representation of a radial shift profile and the positioning of sensor devices with respect thereto;

Fig. 9 is a part perspective view and part schematic diagram of a complete transducer system for deriving a signal (θ) representing the angular displacement of a shaft over 360°;

Fig. 10 shows a modification of sensor placement for exploiting an axial shift profile of profile-shift longitudinal magnetisation;

Fig. 11 shows an embodiment of the invention using enlarged diameter transducer regions;

Fig. 12 is an enlarged end view showing the positioning of the enlarged diameter transducer regions of Fig. 11;

Fig. 13 illustrates another form of enlarged diameter transducer region; and

Fig. 14 shows a modification of Fig. 4 to have narrow eccentric portions modulating the magnetic field emanated by the transducer regions.

Fig. 15 shows an embodiment of a transducer element providing a monotonic response over 360°;

Fig. 16 shows an idealised response curve for a step-type ramp output waveform over two rotations of the shaft;

Fig. 17 shows a modification of the step-type ramp response to use two repeated waveform ramps of differing periods in a 360° cycle;

Fig. 18 shows a configuration of two transducer elements for producing dual-ramp or dual-slope type of waveforms of differing period in a 360° cycle;

Fig. 19 shows idealised symmetrical, dual-slope triangular waveforms of differing period;

Fig. 20 illustrates a cross-section of a transducer region of a shaft given a depth of magnetisation that is a function of angle about the shaft axis;

Fig. 21 shows a cross-section of a shaft that has been case-hardened for wear resistance;

Fig. 22 shows a cross-section of a shaft transducer region in which a magnetic field dependence on angle is achieved by an angle-dependent depth of case-hardening;

Fig. 23a shows side and cross-sectional views of a shaft portion of rolled steel prior to case-hardening;

Fig. 23b shows a side view of the portion of Fig. 23a after heat treatment when being case-hardened; and

Fig. 23c shows a cross-section of the transducer region of the hardened portion of Fig. 23b after machining down.

DESCRIPTION OF THE EMBODIMENTS

Fig. 1 shows a shaft 10 into which a transducer portion 20 is introduced. The shaft 10 is of circular cross-section, though this is not essential, and is mounted for rotation about its central longitudinal axis A-A. The problem to be solved is to measure the angular position of shaft 10 with respect to some datum position. The solution in Fig. 1 is to insert into the shaft a magnetic transducer region 20 which is itself of circular cross-section having an axis B-B which is parallel to and offset from axis A-A of the shaft. The region 20, which may be an integral portion of the shaft, is thus located eccentrically with respect to the shaft axis A-A for angular displacement with the shaft. This eccentric disposition of

the transducer region 20 provides the basis of an angle-dependent measurement of the magnetic field emanated by the transducer region 20 by a magnetic field sensor (MFS) 30 adjacent the region 20 and fixedly mounted at a distance from shaft axis A-A. This embodiment of the invention uses a reduced diameter transducer region in contrast to the enlarged diameter region to be described later.

The sensor 30 is a symbolic indication of the provision of a sensor arrangement which is located in non-contacting relationship with the shaft and transducer region 20 and which detects the external magnetic field emanated by the transducer region. The region stores a permanent magnetisation. The sensor arrangement comprises one or more sensor devices oriented to respond to the emanated flux component in a required direction, e.g. in the direction of axis B-B or radially with respect to that axis. The axial positioning of the sensor device(s) in the axial direction may also be dependent on the kind of magnetisation stored in the transducer region. For example, the profile shift form of longitudinal magnetisation described in WO01/79801 abovementioned is discussed in terms of magnetic field profiles about a centre line C of the transducer region – see Figs. 10 and 11 of WO01/79801 – and to exploit the radial field profile of Fig. 11, a sensor arrangement using pair of sensor devices, one to each side of centre line C may be adopted as is discussed below with reference to Fig. 9. For the purposes of explaining principles underlying the implementation of the present invention, the radial positioning of MFS 30 relative to transducer region 20 is applicable to a single sensor device or to more complex sensor arrangements.

The example of the eccentric positioning of the transducer region 20 shown in Fig. 1 is seen in the end view of Fig. 2 in which the transducer region 20, of a radius r, less than the radius R of the shaft 10, has its axis B-B offset by R-r so as to have a common tangential plane with the shaft at point P.

For convenience of defining angular displacement the normal to the point P, which intersects both the A-A and B-B axes, will be taken as the shaft datum and a perpendicular through the axis A-A intersecting the fixed sensor 30 as the external or sensor datum (Fig. 2a). As will become clear from the following description of this and other embodiments, eccentricities can be used which do not have the transducer region and adjoining portions of the shaft share a common tangential plane.

The sensor 30 is mounted at a fixed distance not less than R from the axis of rotation of the shaft. The sensor is mounted for non-contact measurement of a field component emanated by the transducer region. It is to be assumed that the emanated field of the transducer region 20 is uniform about the axis B-B (referred to as rotationally uniform with respect to axis B-B), whatever the nature of the magnetisation in region 20. The magnetisation will be discussed in more detail below as will the axial positioning and the orientation of the sensor 30. The sensor 30 is connected to appropriate signal conditioning or processing circuitry (SCSP) (not shown in Fig. 1). For example, the sensor 30 may be of the saturating inductor type connected to operate in signal conditioning circuitry such as described in PCT Publication WO98/52063. However, the invention may be practiced with other types of magnetic field sensors such as Hall effect devices and magnetoresistive devices.

Fig. 3 shows a graph of signal output V_o from the sensor circuitry in Volts (V)as a function of the angle θ of shaft 10 about its axis A-A. The zero angle is the position shown in Fig. 2a and Fig. 3 shows the output variation with the shaft rotating clockwise (CW). The signal varies in a cyclic and essentially sinusoidal manner through 360° of rotation about some mean level V_m. The signal will be at a maximum, V_{max}, at 270° where the shaft datum coincides with the external sensor datum, the closest approach of the transducer region 20 to the sensor 30 and be at a minimum, V_{min}, at 90° from that position. As will be readily seen from the symmetry of Figs. 2 and 2a, there are equal signal outputs for pairs of shaft angles equally displaced about the shaft datum. Thus as so far described a monotonic relationship of signal output exists over a range of angular displacement restricted to a range of angle not exceeding 180°, specifically in Fig. 3 90°-270° and 270°-90° but there is ambiguity if angular position is required to be measured over the full 360° range.

The output signal is not strictly as shown in Fig. 3 with respect to the V_m level taken as the mean of the complete 360° waveform. Due to the variation of detected field as an inverse function of the distance of the sensor to the transducer surface, the maximum half-cycle has a greater excursion than the minimum half-cycle. The half-cycle amplitudes can be equalised using analogue non-linear amplifiers or linearizing applied to digital (numerical) values. The effect of different amplitude positive- and negative-going half-cycles is to shift the mean level upwards so that the two half-cycles do not have equal angular periods with respect to the shifted mean value.

The ambiguity pointed out above can be resolved by introducing a second transducer element angularly displaced from the element 20. Figs. 4 and 5 show such an arrangement.

Figs. 4 and 5 are similar to Figs. 1 and 2 but show the introduction of another offset transducer region 22 and its associated sensor 32. The region 22 is axially spaced from region 20, there being an intervening portion 10a of the shaft between them. Each transducer element 20 and 22 thus has portions of the shaft 10 adjoining it on each side. The structure and arrangement of region 22 is identical with that of region 22 except for the difference of its angular position about axis A-A. It is angularly offset by 90° with respect to region 22. However its associated sensor 32 is positioned at the same angle about shaft axis A-A as sensor 30, though axially spaced to coact with region 22. Sensor 32 is connected into signal conditioning circuitry the same way as sensor 30. The sensors operate separately to develop respective output signals as will now be described. As already indicated the relevant parameters pertaining to region 22 are identical to those pertaining to region 20 described above except that the offset is at a different angle, about axis A-A and specifically the offset for region 22 is shown as being at 90° to that for region 20. While the respective internal datums for regions 20 and 22 extending to points P_1 and P_2 respectively are at 90°, the sensors 30 and 32 share the same external sensor datum.

Fig. 6 shows the respective signal output curves denoted [30] and [32] which are spatially 90° out of phase. The curves are shown for a zero angle position which is that shown in Figs. 4 and 5 with the shaft 10 rotating counter-clockwise (CCW). As will be described further shortly, these angularly spatially

displaced curves enable the above-noted ambiguity to be resolved and measurement to be made over a full 360°.

It will also be seen from Fig. 5 that if the sensor 32 were displaced by a given angle about axis A-A from sensor 30 then curve [32] would be displaced from its showing in Fig. 6 by the same angle. Similarly if the regions were displaced by a given angle, then the curves [30] and [32] would be similarly displaced from the showing of Fig. 6. Consequently it will be understood that the 90° angular offset between regions 20 and 22 is not essential. Other offsets are possible provided that a corresponding adjustment of the angular offsets of the sensors 30 and 32 is made to achieve the 90° spatial separation of the output signals or whatever angle is desired.

If the two regions 22 and 20 are given a zero angular offset, then the sensors 30 and 32 are angularly offset by 90°. In this case the regions are aligned axially. The same result can be realised by using a single transducer region with two sensors 90° offset from one another.

In the embodiment of Fig. 4, the two transducer regions 20 and 22 are separated by a land or portion 10a of the shaft 10. However, the two regions could be formed along one single host section of reduced radius r and even share a common pole portion by having the two transducer regions of opposite axial polarity. It is also possible to introduce guard or keeper regions into the transducer region as is described in WO99/56099. Guard regions for longitudinally magnetised keeper regions may be circumferentially polarised.

Reverting to the preferred arrangement of Fig. 4 in which the sensors 30 and 32 are at the same angular position (though axially spaced), two signal

outputs can be converted into unambiguous angular information. At its simplest level, the ambiguity in the output signal from one transducer element is resolvable with the aid of the sign of the output signal from the other transducer element. The conversion to an angle-representing digital output may be implemented in a commercially available integrated circuit, namely the Sine/Digital Angular Encoder iC-NG available from iC-Haus GmbH., Am Kuemmerling 18, D-55924, Bodenheim, Germany. This device is a monolithic analog-digital converter which determines the angle value of two sinusoidal input signals phase-shifted at 90° with a given resolution and hysteresis. The device may be adapted in its use for conversion of non-sinusoidal input signals.

As already stated above, the invention can be implemented with transducer elements magnetised in various ways. One particular implementation uses profile-shift longitudinal magnetisation, the nature of which is described in aforementioned WO01/79801.

The magnetisation of transducer region 20 in Fig. 4 in accordance with profile shift longitudinal magnetisation is outlined below. This form of longitudinal magnetisation is an annulus of magnetisation extending about the transducer element axis (e.g. axis B-B for region 20). The annulus is obtained by rotating the transducer region about its own axis (not the axis A-A of the shaft) in the presence of a magnetising arrangement which encodes or programs the transducer region (sensors host) with the desired magnetisation.

Preferably the sensor host should be magnetically-cleansed before being encoded, the sensor host being the shaft or other part in which the transducer element is incorporated, and particularly where the shaft and transducer region

are integral.. This may generally be referred to as a de-gaussing procedure intended to remove unknown stray fields that may exist within the ferromagnetic material of the sensor host. This may be expressed in terms of ensuring that the magnetic direction of individual grains of the sensor host material is random so that no grouping of magnetic domains in any particular direction exists.

The magnetisation to be induced in the sensor host, that is the part of the shaft of Fig. 1 that will become the transducer region, is to be permanent with no or little self-demagnetisation over time. While the magnetisation induced in the shaft has to be sufficient to create the desired annular magnetisation described below, it is also desirable that the emanated magnetic field is at a low enough level to avoid attracting magnetisable particles that might stick to the surface of the sensor host and modulate the desired uniform field around the host.

Fig. 7 shows a sensor host 40 as a solid circular cylinder of ferromagnetic material, which has been magnetically cleansed and into which a magnetised region 42 is to be induced. The region 42 is magnetised by a pair of like but oppositely-poled magnets 44a, 44b which are preferably brought from a distance to a position closely adjacent the sensor host at which substantial magnetic flux will traverse the proximate surface zone of region 42 in an axial direction. The magnets dwell at this closely adjacent position for an interval before being moved away, the sensor host 40 being rotated about its longitudinal axis A-A all the while. The magnets may be magnetically connected at their distal ends by a member 46 providing a low reluctance path to enhance the magnetic flux entering the sensor host. The magnets 44a, 44b should have an axial width w which is substantially greater than the axial gap g

between the magnets: for example a ratio of w/g of about 7 has proved satisfactory. In addition the thickness of the magnets in the circumferential direction is also substantially less than the axial width w: for example a ratio of w/t of 3-4 has proved satisfactory. The magnetised region 42 has a North and South end portions about a centre line 50. What is of interest is the external flux that is emanated to extend generally axially between the N and S portions, the external flux itself forming an annulus about the sensor host. More particularly what is used in measurement is the profile of the external magnetic field, the profile being the magnetic field measured as a function of axial position at a constant radial distance in moving a sensor in the axial direction adjacent the surface of the host. Two profiles are measurable, one of the axially-directed component of that external field and the other of the radially-directed component. These are measured with the aid of an axially or radially oriented sensor respectively. What has been surprisingly found is that these profiles exhibit an axial shift in response to applied torque, which characteristic is used as the basis of the torque measuring arrangement described in WO01.79801.

The torque measurement possibility is not of direct interest here but the radial profile can be exploited for angle measurement. Fig. 8 shows the form of a radial profile of magnetic field strength (magnetic flux density) B as a function of axial position. The graph shows the distribution about the centre line 50 of the transducer region. The profile falls to zero and the field polarity reverses direction at the centre line. To exploit this characteristic the sensor 30 of Fig. 1 (or each of the sensors 30 and 32 of Fig. 4) is realised in the form of two sensor devices 30a, 30b on opposite sides of the centre line 50. The dot ends of

devices 30a, 30b indicate like polarity of response to an applied magnetic field. To obtain an additive response to the profile of Fig. 8, the devices 30a, 30b are connected in series, either dot end or non-dot ends joined, into a signal conditioning circuit of the kind mentioned above. Because the sensor devices 30a, 30b are subject to fields of opposite polarity they are in a summing connection as regards these fields to produce a combined output signal V_o. It will be noted that over the linear portion of the profile the output signal V_o will be independent of axial position for a fixed axial spacing of the sensor devices. This series connection, however, provides a rejection the radial component of a common mode field having the same polarity at both sensor devices. The component of the Earth's magnetic field in the radial direction is an example of a field whose effects are cancelled by the series connection of the sensor devices 30a, 30b.

It will be understood that for a transducer system having two transducer regions with different angularly disposed offsets such as illustrated in Figs. 4 and 5, each transducer region is magnetically encoded and has a coacting pair of sensor devices as has been described with reference to Figs. 7 and 8. The magnetising of each region 20, 30 is done in accord with region 42 in Fig. 7 with the region being rotated about its own individual axis.

Fig. 9 illustrates the complete transducer system incorporating the techniques described above. It follows Figs. 4 and 5 in having the two transducer regions 20 and 22 (transducer A and transducer B) having the profile characteristic of Fig. 8 and with respective sensors 30 and 32, each comprised

of a pair of sensor devices as in Fig. 8. The devices of each pair are connected in series into a signal conditioning circuit 52 and 54 respectively so that they sum as regards the detected transducer field but cancel as regards a common mode field. The signal conditioning circuits produce output signals V_A and V_B respectively having the 90° phase relationship of Fig. 6. The two signals are applied, after a linearizing operation if necessary, to a resolver 60, such as the iC-NG mentioned above to produce the output angle signal V_θ representing the angle of the shaft 10 about axis A-A over the full 360°.

Fig. 10 illustrates a modification of the transducer system for detecting an axially-directed magnetic field component. Such a component arises with various forms of magnetisation as already described. In Fig. 10, the transducer regions 20' and 22' may be circumferential-sensing longitudinal magnetisation as described in WO01/13081 abovementioned. The sensor devices 30' and 32' are axially oriented to respond to the inherent axial component of external magnetic field associated with this form of magnetisation. The centre line 50 of the region is of no particular interest in this case. Axially oriented sensor devices are also applicable to other magnetisations which provide axially-directed field components including the profile-shift longitudinal magnetisation already discussed. To best use the axial component in this last case the sensor devices are to be located to one or other side of the centre line 50.

The embodiments so far described have the transducer region(s) of lesser diameter than the shaft thereby reducing the mechanical strength of the shaft at the transducer elements. This strength reduction can be avoided by using transducer regions whose radius r is greater than that (R) of the shaft.

Such an arrangement is shown in Figs. 11 and 12 in which the transducer regions 70 and 72 are of greater diameter than the shaft 10. They are again eccentrically disposed with respect to the shaft axis, that is their individual axes are offset from the shaft axis. Fig. 12 illustrates the angular positioning of the regions in an end view of the shaft transducer region 72 of axis B_2 and radius r offset from the shaft 10 of radius R by r-R so that the two have a common tangential plane at point P_1. The transducer region 70 is similarly disposed with an axis B_1 but with an angular offset of 90° about shaft axis A-A with respect to region 72 and sharing a common tangential plane with the shaft at P_2.

Fig. 13 illustrates how an enlarged transducer region such as shown in Figs. 11 and 12 can be realised without machining of the shaft 10. In Fig. 13 a shaft 10' is to have a transducer element formed thereat at region 70', the transducer element being offset from the axis of rotation A-A of shaft 10' so as to rotate eccentrically therewith. The transducer region 70' is magnetised to provide, in the absence of an additional measure, an external field uniform about the shaft axis A-A and this field has an eccentric modulation, applied to it. To this end an eccentrically-apertured circular ring 74 is close-fitted on the shaft - which is shown to be of circular cross-section but need not necessarily be so - to provide the transducer element having a ring providing a circular circumferential surface of larger diameter whose axis is offset from the shaft axis A-A. Thus the ring 74 has a central aperture 76 which matches the cross-section of the shaft 10' and which is offset from the axis of the outer circumference of the ring. The ring has an axial length l substantially less than the axial length of region 70' but its presence and ferromagnetism are sufficient to modulate the magnetic field in

the vicinity of the ring as a function of shaft angle to provide the equivalent of the eccentric offset previously described. The sensor cooperating with the transducer element (70' + 74) will be located near the ring to detect the modulated field pattern.

An alternative would be to make the ring 74 of extended axial length so as to form a collar about the shaft capable itself of being magnetised to provide a transducer element of itself or in conjunction with portions of the magnetised shaft 10'. A transducer such as 70 could be realised by having a long enough collar. A longer collar could comprise a sequence of mating ring sections of lesser axial length.

If the collar were of sufficient radial depth so that no reliance is placed on the shaft material to support the magnetic field, the collar or a pair of angularly displaced collars could provide a transducer arrangement equivalent to Fig. 11 on a non-magnetic shaft.

Reverting to the use of a ferromagnetic ring 74 to locally modulate the external field of a transducer region in the shaft 10' it is contemplated that the ring could have a magnetic property other than ferromagnetism to provide the desired modulation.

The concept of modulating the field from a transducer region formed in the shaft itself can be applied to the reduced diameter constructions described earlier. An example is shown in Fig. 14. Here the shaft 10 is formed in a similar manner to Fig. 4 to provide larger diameter shaft portions 10a, 10b, 10c and eccentric reduced diameter portions 80 and 82. However, the transducer regions 84 and 86 respectively extend axially beyond portions 80 and 82. The

centre line 50a, 50b of each region is shown lying on a circumference of a respective reduced diameter region. The axial length of each eccentric reduced diameter portion may be small - less than 1 mm. - to detectably modulate the magnetic field emanated by the associated transducer region. Each transducer region including the reduced diameter portion of it may be magnetised in a single encoding operation as described with reference to Fig. 7.

In discussing the use of one or more regions eccentric to the shaft, it will be understood that the eccentricity about the shaft axis provides the required angle-dependent variation of magnetic field. It is not necessary that an eccentric portion shares a common tangent plane with the adjoining shaft portion(s). One example is to have the radii R and r the same but having their centres offset.

Embodiments of the invention described above have transducer regions which individually have an ambiguity if used over a full 360°. Furthermore, the surface from which the detected magnetic field is emanated is itself circular but eccentric with respect to the shaft axis. An approach to non-ambiguous measurement using a single transducer element will now be described.

Fig. 15 shows a ramp form of transducer surface providing a monotonic variation of output signal over 360°. The ramp in this case is a variation of radial dimension R_θ with angle θ. In Fig. 15 a shaft 90 rotatable about axis A has closed fitted to it a ring 92 having a surface 94 whose radial distance R_θ from axis A is a monotonic, for example linear, function of angle θ about axis A. It will be realised that ring 92 could be machined as an integral portion of the shaft. However, in the embodiment of Fig. 15 it is proposed that a shaft of ferromagnetic material and of circular cross-section be magnetised with a

rotationally uniform field such as described with reference to Fig. 7 and the ring 92 be of a high permeability, magnetically soft material so that the annular field remanently stored in shaft 90 permeates ring 92 to emanate from surface 94 a magnetic field detectable by a fixed sensor 30 adjacent the ring 92. In practice the ring will have some base minimal radial thickness at the zero θ point. The detected field will be an unambiguous inverse function of the ramp function over a full 360° though it is recognized that at the point 98 there is a step function which may lead to an unsatisfactory region of response. This could be overcome by a second ramp function transducer bridging this region. Fig. 16 illustrates in idealised form the kind of output signal V_0 achievable with a single transducer element operating over 360°. Two cycles of rotations of the shaft 90 are shown.

In Fig. 15 and also in Fig. 13, the ring fitted on the shaft has been taken as completely encircling the shaft. Where a range of angular measurements less than 360° is sufficient, the ring need not be complete but may have a gap in it which may assist in fitting it on the shaft.

Another possibility is to use a transducer having two transducer elements each of which provides a periodic ramp function over 360° but whose periods (in angle) are different so as to resolve ambiguity. This is illustrated in Fig. 17 where a series of ramps are shown as a function of angle θ. One element provides ramps 100 (chain line): the other provides ramps 102 (full line). The ramp periods are in an (n): (n + 1) relationship over the 360°, specifically 4:5 is illustrated.

The step function generated by the single ramp transducer element of Fig. 15 or multi-ramp element designed to provide the kind of signal shown in Fig. 17 can be avoided by the adoption of other waveforms such as triangular in which there are no step points though there may be discontinuities. The latter tend to become smoothed by the sensor resolution in any event. However, the provision of a dual-ramp or dual-slope type of waveform does reintroduce ambiguity since the same output value is obtained at a first angle on the up-ramp and a second angle on the down-ramp.

Fig. 18 illustrates the configuration of two transducer elements fixed to a shaft 110 having a pair of axially spaced magnetised regions. One element 112 has a generally triangular configuration with three "triangular" lobes of equal period covering 360°. The other element 114 has four lobes of equal period in a generally quadrilateral configuration covering 360°. In each configuration the individual lobes are symmetrical with equal up-slope and down-slope portions. The arrangement shown can provide unambiguous measurement over 180°.

Fig. 19 represents idealised output curves for respective sensors operating with an n : n + 1 period relationship (3:4 is shown) for triangular responses rather than the step function responses of Fig. 17. The responses are shown as curves of repeated triangular waveform 116 and 118 respectively.

The structure of a transducer assembly to generate the kind of output waveforms shown in Figs. 17 and 19 can utilise the technique illustrated in Fig. 15. The shaft, preferably circular, is magnetised to generate of itself an emanated field which is rotationally uniform and the desired modulating waveform is obtained by affixing an appropriately shaped part to the shaft. Thus

in Fig. 18 shaped modulating parts 112 and 114 can be affixed to respective regions of shaft 110 that have been uniformly magnetised about the shaft axis.

The signal processing of the output signals of Figs. 17 and 19 can be implemented by calculation using the known relationship between the waveforms as well as their variation with angle. Another approach is to store corresponding values in look-up tables, obtained with the aid of a calibration procedure if desired. Look up tables, obtained by a calibration procedure if desired, can also be applied to the embodiment of Fig. 15 and also to earlier described embodiments.

Yet another approach to angle measurement is to use a series or sequence of permanent magnet elements around the circumference of the shaft or other part whose angular position is to be measured. The sequence of magnets is used to generate a repeated magnetic field waveform about the axis in the manner discussed above. Such a sequence of permanent magnets is disclosed in above-mentioned WO00/58704 at Fig. 10 where the permanent magnets are used as discrete elements for counting as previously discussed. The individual magnets may be radially or circumferentially oriented. In the disclosure of WO00/58704 relating to Fig. 10 two identical, aligned rings or annuli of magnets are shown. By making the rings of different waveform period in accord with the teaching given above with reference to Figs. 17 and 19, for example, and by applying appropriate calculating techniques to the detected waveforms - in contrast to counting cycles of the waveform and the cycle rate - an angle-indicative output signal can be derived.

Another approach to angle measurement will now be described. It is based on the degree of rotational uniformity of magnetisation of a shaft, a subject which has already been discussed. More particularly it is proposed to introduce a controlled degree of non-uniformity into the magnetisation of a shaft, a property which may be referred to as non-rotational uniformity (NRU). The NRU establishes an angle-dependent external field about the shaft. It can be practised on shafts of circular cross-section without the need to machine the shaft or add field-modulating parts to it. In many applications where torque is applied to turn the shaft, though not necessarily to continuously rotate it, engineering considerations dictate that the shaft be of a uniform cross-section along its length, commonly a circular cross-section.

A degree of non-rotational uniformity can be achieved by a deliberate non-uniform magnetisation of the shaft to create a stored annulus of magnetisation which has an external magnetic field profile such as shown in Fig. 20 which shows a circular cross-section of a shaft 120 which has been given a permanent magnetisation in a surface-adjacent, annular region 122, e.g. a longitudinal magnetisation, whose external field strength is represented by a constant field strength profile 124. The profile exhibits an eccentricity with respect to the shaft axis A to produce a response from sensor 130 which is similar to that illustrated in Fig. 3.

The eccentric magnetic profile can be realised by magnetising the shaft to a depth that is a function of the angular position of the shaft. To this end the magnetisation procedure above-described with reference to Fig. 7 and described in WO01/13081 and WO01/79801 can be modified to more the

magnetising source (permanent magnet or electromagnet) toward and away from the shaft surface as a controlled function of the angular position of the shaft about its axis A.

The depth of magnetisation varies as a function of angle about axis A between a region 122a of maximum depth and a region 122b of minimum depth. A point P' at the minimum may be used to define a datum.

Another process for achieving a desired NRU is obtainable with case-hardened steel shafts such as circular cross-section shafts of FV 250B high performance steel. It is common practice that such shafts are case-hardened to enhance their performance, particularly wear resistance, in a given engineering application. The cross-section of such a shaft 140 is illustrated in Fig. 21 having a case-hardened peripheral region as indicated at 142. The case-hardened region 142 has somewhat different magnetic properties to those of the remainder of the shaft. It magnetises more strongly in this case, i.e. develops a higher level of remanent stored magnetism. In practice, of course, there is a graded transition between the case-hardened region and the interior region of the shaft. A controlled NRU is achievable with a shaft having an integral annular magnetised region wherein the case-hardened region is eccentric about the shaft axis as illustrated in Fig. 22 which shows a case-hardened region 142' which is eccentric about shaft axis A and so as to be so eccentric in depth with respect to the shaft surface.

The transducer region of shaft 140 having the eccentric case-hardened region 142' can be permanently magnetised by a magnetisation source held adjacent the shaft at a constant distance from the surface, in contrast to the

procedure for magnetisation of region 142 of Fig. 20. Due to the differential magnetic property of the annular case-hardened zone 142' as compared to the interior remainder of the shaft, the effect of the magnetised region 142' is to emanate an eccentric magnetic field about axis A similar to that represented by profile 124 in Fig. 20.

The region 142' supports a higher level of magnetisation than the remainder of shaft 140 so that a region 142'a of maximum depth of zone 142' the highest level of emanated field will be generated. The lowest level of emanated field is generated from the region 142'b of minimum depth. The depth increases continuously from region 142'b at which the datum point P' can be defined to the region 142'a. The result is that the sensor 130 provides an angle-dependent output signal similar to that provided by sensor 130 in Fig. 20. The output signal is of a form that is similar to Fig. 3, Figs. 20 and 22 providing essentially the same result as the transducer region of Figs. 1, 2 and 2a but the transducer region is an integral portion of a shaft of simple cross-section, e.g. circular, without any complex machining being necessary.

The process forming the eccentric case-hardened region of the transducer element of Fig. 22 comprises the steps described below which are explained with reference to Figs. 23a to 23c.

Fig. 23a shows a portion of a straight length of a steel shaft 150 of circular cross-section in which a transducer region 160 is to be provided. The shaft may be of the FV250B steel previously mentioned and at the step illustrated in Fig. 23a, the shaft has been formed from a continuous stock that has been through stages of a rolling mill in which the stock has been

progressively drawn down having started at an elevated temperature and finally exiting the mill at a relatively low temperature at which the internal structure of the material is set. The final rolling produces a straight length of stock but in which tensions exist acting transversely of the longitudinal axis of the stock. The shaft at this step is relatively soft and its surface does not have sufficient wear resistance for the application in which the shaft is to be employed.

As is well-known, resistance can be improved by case-hardening. The shaft 150, which may also have now been subjected to other fabrication procedures, is case-hardened to produce an annular surface-adjacent case-hardened zone having a cross-section at any point along the length of the shaft comparable to zone 142 in Fig. 21. However, the heating required by the case-hardening, e.g. to a low red heat, enables the transverse tensions in the shaft to release by causing a transverse bending of the shaft as shown in the side view of Fig. 23b in which the bent shaft is denoted 150'. For the purposes of clarity of illustration the bending of the shaft is very greatly exaggerated and the depth of hardening also exaggerated.

The bent shaft 150' is now machined down by roation about an axis A'-A' nominally aligned with axis A-A in Fig. 23b. However it will be recognised that if the shaft portion 150' shown in Fig. 23b were to be supported at its ends for rotation about an axis A-A' aligned centrally of the cross-section at each end, the middle region 160 where the transducer element is to be provided would rotate eccentrically about this axis.

Fig. 23c illustrates to a different dimensional scale than that of Fig. 23b) the effect of the machining at a cross-section within region 160. The cross-

section 160a has its own centre denoted A. The cross-section 160a is rotated for machining about the offset centre A'. The machining acts at a level indicated by dash-line C-C to reduce the shaft to a circular cross-section 160b which is eccentric with respect to the original cross-section. The inner boundary of the case-hardening is indicated at 160c and this is at a substantially constant depth from the surface of the original cross-section 160. As above-mentioned this boundary is notional in that there is a graded transition. The boundary is also eccentric with respect to axis A'. What remains after machining is an eccentric zone 162 of case-hardened material within the new 160b. This provides a zone of case-hardened material equivalent to the zone 142' in Fig. 22. It will be understood that the reduction in the cross-section consequent upon the machining of the shaft to a truly straight length is done with the desired mechanical purpose of the case hardening as the main objective. Thus sufficient hardened material must be retained around the whole cross-section leaving sufficient material even at minimum depth region 122b in Fig. 22.

Claims

1. A transducer for measuring the angle of displacement of a part about an axis comprising:

a magnetic transducer element mechanically coupled to said part to move therewith in angular displacement of the part about said axis;

said transducer element being magnetised for emanating a magnetic field which varies as a function of angle about the axis over at least a range of angular values; and

a sensor disposed adjacent said transducer element to detect the emanated magnetic field and provide a signal dependent on the detected field which represents the angle of displacement about said axis.

2. A transducer as claimed in Claim 1 in which said transducer element has a surface extending about said axis from which said magnetic field is emanated, the radial distance of said surface from said axis varying as a function of angle about the axis.

3. A transducer as claimed in Claim 2 in which said emanated magnetic field, as measured at a given distance from said surface, is substantially uniform as a function of angle about said axis.

4. A transducer as claimed in Claim 2 or 3 in which said transducer element comprises a first portion of circular cross-section magnetised with a remanent magnetisation which emanates a magnetic field which is essentially uniform about the axis of said cross-section, and a second portion of magnetically soft material and having said surface, said second portion being secured to said first

portion in good magnetic connection therewith to transmit magnetic flux emanated by said first portion through said second portion to provide a magnetic field emanated at said surface.

5. A transducer as claimed in Claim 4 in which the axis of the cross-section of said first portion is offset from the axis of angular displacement of said part.

6. A transducer as claimed in Claim 5 in which the offset axes are parallel.

7. A transducer as claimed in Claim 2, 3, 4 or 5 further comprising a second transducer element which has a second surface extending about said axis of angular displacement of said part, the radial distance of said second surface from said axis varying as a function of angle about the axis and a second sensor disposed adjacent said second transducer element to detect the emanated magnetic field, the first-mentioned and second transducer surfaces each being a periodic function of angle about at least an angular range about said axis, the surfaces having different angular periods.

8. A transducer as claimed in Claim 1 in which the different angular periods have an n to (n +1) relationship expressed over 360°.

9. A transducer as claimed in Claim 2, 3 or 4 in which said surface defines a ramp as a function of angle.

10. A transducer as claimed in Claim 9 in which said ramp extends over 360°.

11. A transducer for measuring the angle of displacement of a part about an axis comprising:

a magnetic transducer element mechanically coupled to said part to move therewith in angular displacement of the part about said axis;

said transducer element being magnetised for emanating a magnetic field which has a predetermined relationship of emanated field as a function of angle about an offset axis parallel to and offset from said part axis;

a sensor disposed adjacent said transducer element to detect the emanated magnetic field and provide an output signal dependent on the detected field which is a function of the angle of displacement of said part about the part axis.

12. A transducer as claimed in Claim 11 in which said output signal is a monotonic function of the angle of displacement over at least a range of angle.

13. A transducer as claimed in Claim 1 in which said output signal is a monotonic function of the angle of displacement over 180°.

14. A transducer as claimed in Claim 11, 12 or 13 in which said sensor is fixed with respect to said part axis and affords non-contact sensing of the field emanated by said transducer element.

15. A transducer as claimed in any preceding claim in which said transducer element emanates a uniform field distribution about said offset axis.

16. A transducer as claimed in any preceding claim in which said transducer element has a circular cross-section.

17. A transducer as claimed in any preceding claim in which said part is a shaft mounted for rotation about a longitudinal axis constituting said part axis.

18. A transducer as claimed in Claim 17 in which said longitudinal axis is the centre axis of the shaft.

19. A transducer as claimed in Claim 17 in which said transducer element comprises a portion of the shaft eccentrically disposed in relation to the adjoining portions of the shaft.

20. A transducer as claimed in Claim 19 in which said transducer element portion and the adjoining portions of the shaft are of circular cross-section, said transducer element portion having a different diameter to that of the adjoining portions.

21. A transducer as claimed in Claim 9 in which said transducer element portion is integral with the adjoining portions.

22. A transducer as claimed in any preceding claim in which said transducer element is magnetised with profile-shift longitudinal magnetisation and said sensor comprises two sensor devices disposed to sense the emanated radial component of the longitudinal magnetisation, the sensor devices being disposed on opposite sides of the centre line of the longitudinal magnetisation and connected in series additively with respect to the radial components sensed thereby.

23. A transducer for measuring the angle of displacement of a part about an axis comprising first and second magnetic transducer elements mechanically coupled to said part to move therewith in angular displacement of the part about said axis;

each of said first and second transducer elements being magnetised for emanating a magnetic field which has a predetermined relationship of emanated field as a function of angle about a respective offset axis parallel to and offset from said part axis;

the offset axes being mutually angularly offset about said part axis;

first and second sensors disposed adjacent said first and second transducer elements to detect the respective emanated magnetic fields and provide first and second output signals respectively dependent on the respective detected field, each of which is a function of the angle of displacement of said part about the part axis.

24. A transducer as claimed in Claim 23 in which the angular offset of the offset axes is 90°.

25. A transducer as claimed in Claim 23 or 24 in which the respective offset axes of said first and second transducer elements have the same offset from said part axis.

26. A transducer as claimed in Claim 22, 24 or 25 in which said transducer elements are essentially identical other than for said angular offset of their respective offset axes.

27. A transducer as claimed in Claim 26 in which said first and second sensors are identical and disposed in identical non-contact relationship with respect to said first and second transducer elements.

28. A transducer as claimed in any one of Claims 23 to 27 further comprising means for combining said output signals to provide an unambiguous

measurement of the angle of displacement of said part over 360° about said part axis.

29. A transducer as claimed in any one of Claims 23 to 28 in which each of the first and second transducer elements and the respective one the first and second sensors is as defined for the transducer element and sensor as set forth in any one of Claims 3 to 22.

30. A transducer for measuring the angle of displacement of a part about an axis comprising a magnetic transducer element mechanically coupled to said part to move therewith in angular displacement of the part about said axis;

said transducer element being magnetised for emanating a magnetic field which has a predetermined relationship of emanated field as a function of angle about an offset axis parallel to and offset from said part axis;

first and second sensors disposed adjacent said transducer element to detect the emanated magnetic field and provide first and second output signals respectively dependent on the detected field, each of which signals is a function of the angle of displacement of said part about the part axis; and

said sensors having an angular offset, preferably 90°, about said part axis.

31. A transducer as claimed in Claim 1 in which the transducer element is an integral portion of said part and said portion is given a magnetic property in a surface-adjacent zone about said axis, which property is different from the remainder of said part, said surface zone having a radial depth about said axis which is a function of angle about said axis.

32. A transducer as claimed in Claim 31 in which said surface-adjacent zone is the zone in which the transducer element is magnetised.

33. A transducer as claimed in Claim 31 in which said surface-adjacent zone is a case-hardened zone of a steel part and is magnetised.

34. A transducer as claimed in Claim 31, 32 or 33 in which said surface-adjacent zone has a minimum radial depth at a point substantially radially opposite the point of maximum radial depth, the depth increasing as a function of angle from the point of minimum depth to the point of maximum depth.

35. A transducer element for a transducer, the transducer element being as set forth in any preceding claim.

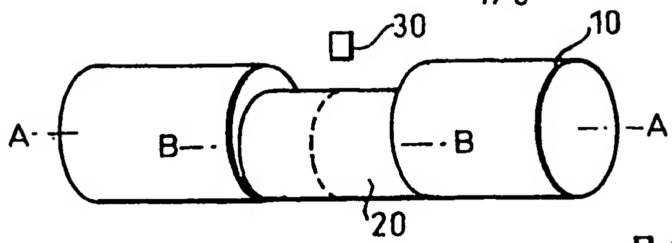


Fig.1.

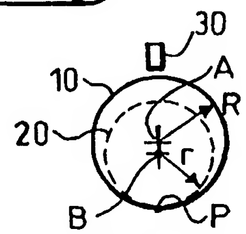


Fig.2.

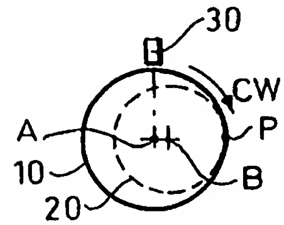


Fig.2a.

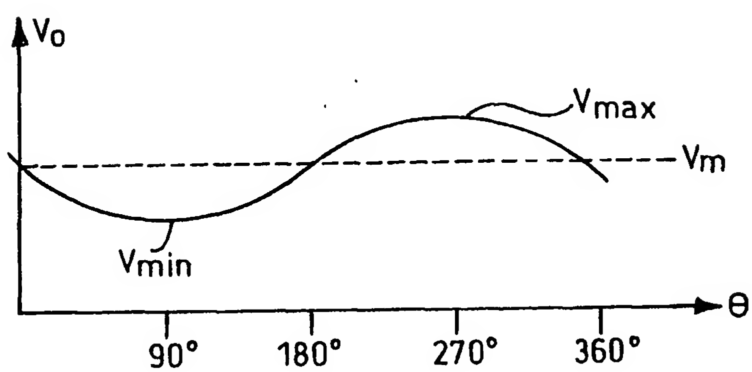


Fig.3.

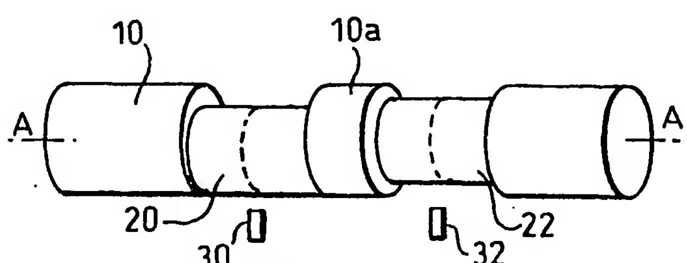


Fig.4.

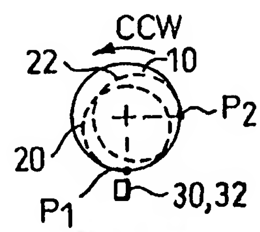


Fig.5.

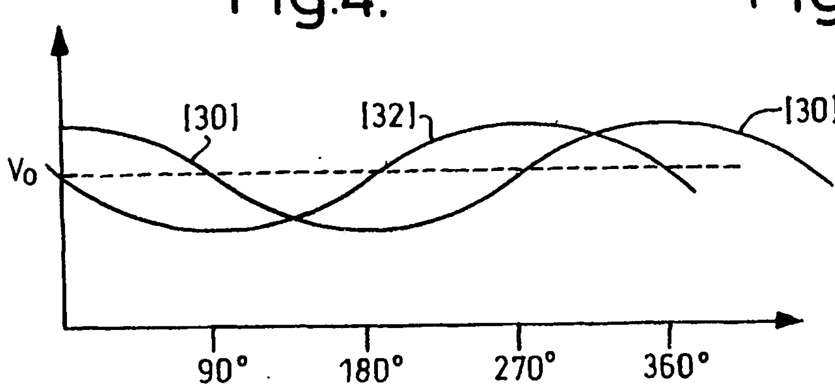


Fig.6.

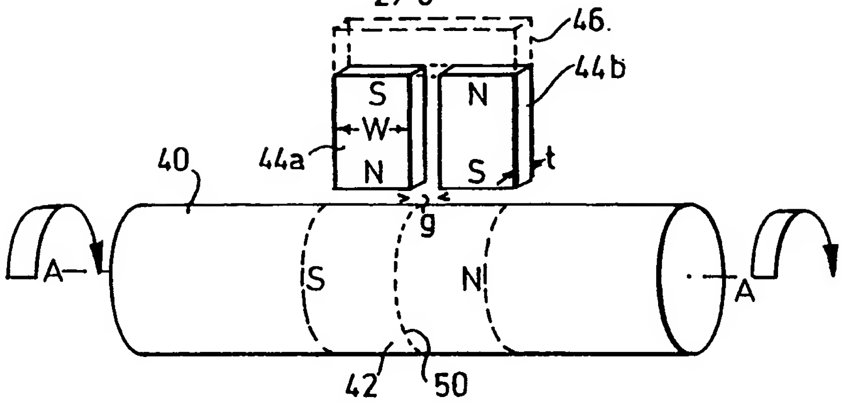


Fig.7.

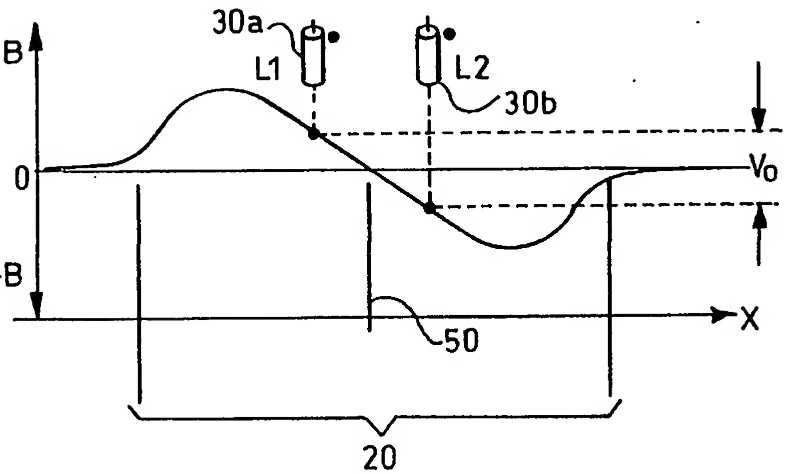


Fig.8.

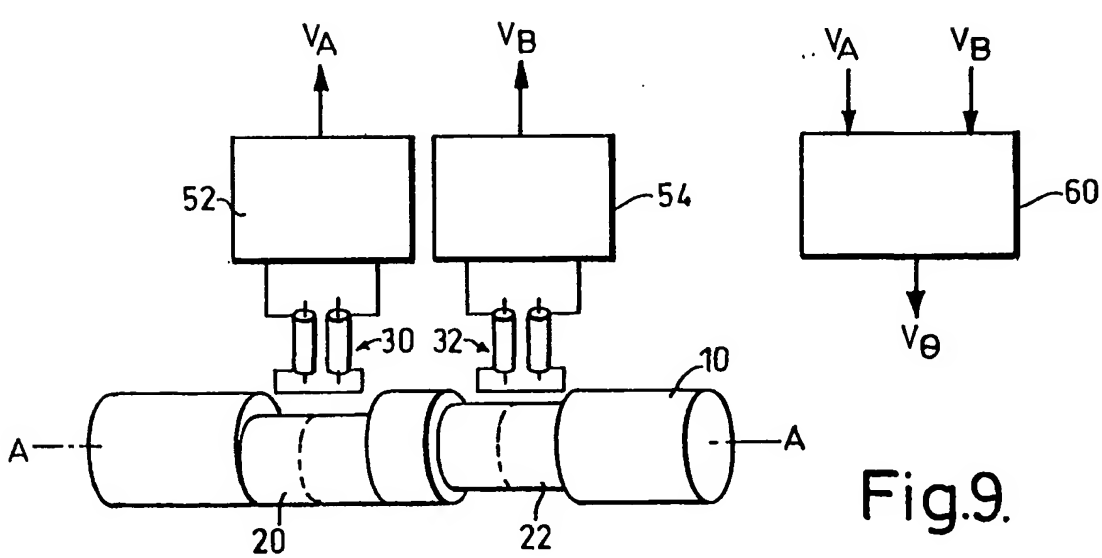


Fig.9.

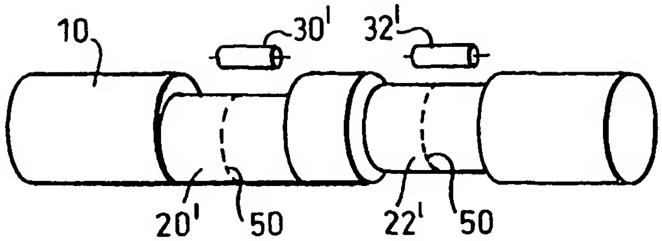


Fig.10.

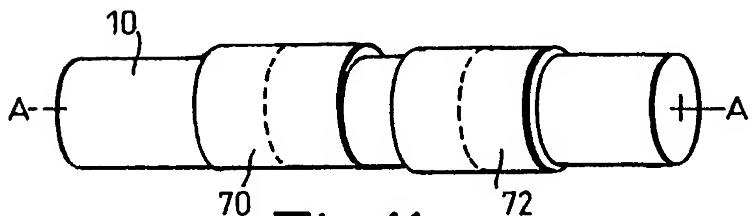


Fig.11.

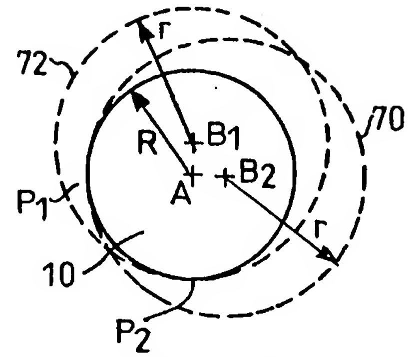


Fig.12.

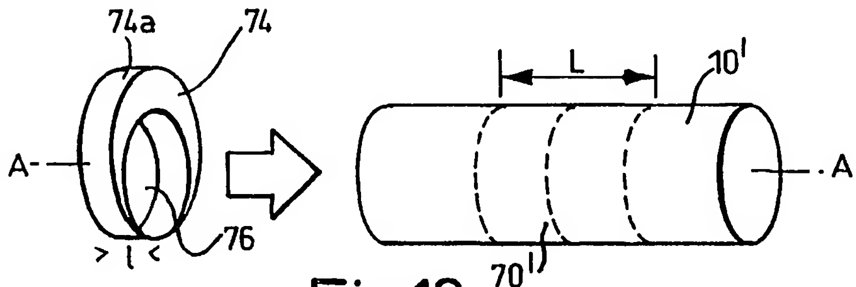


Fig.13.

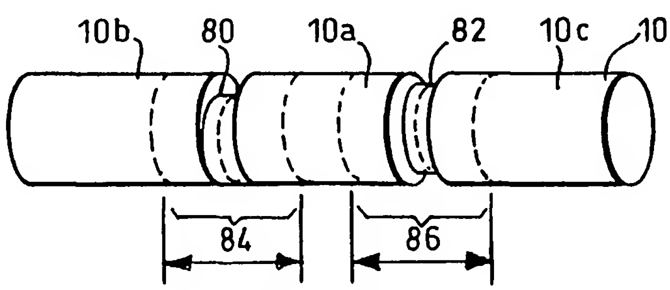


Fig.14.

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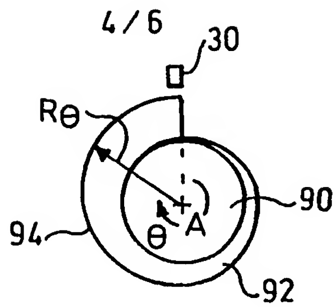


Fig.15.

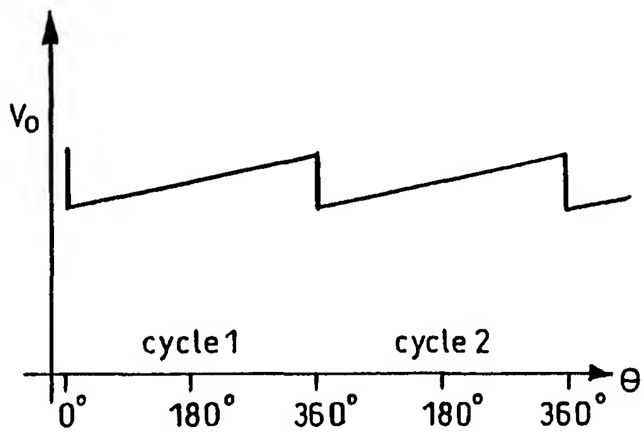


Fig.16.

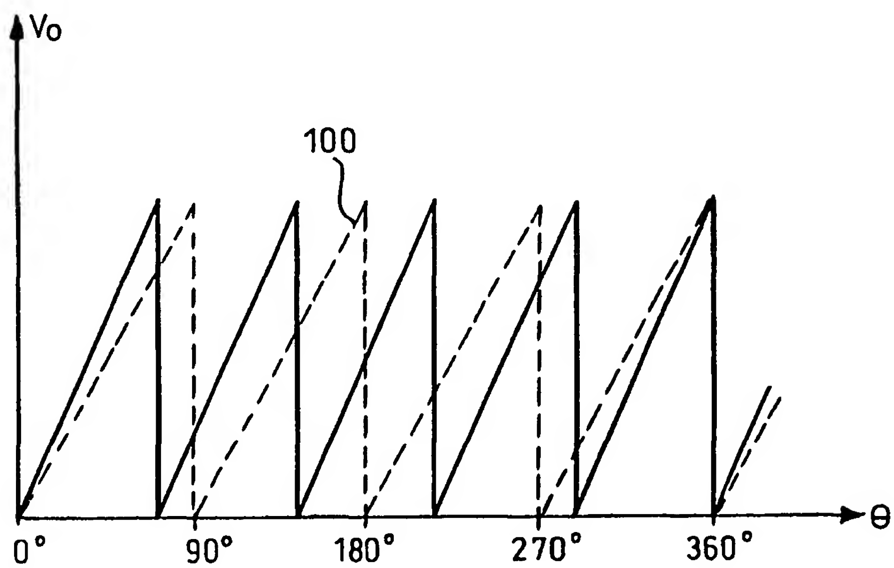
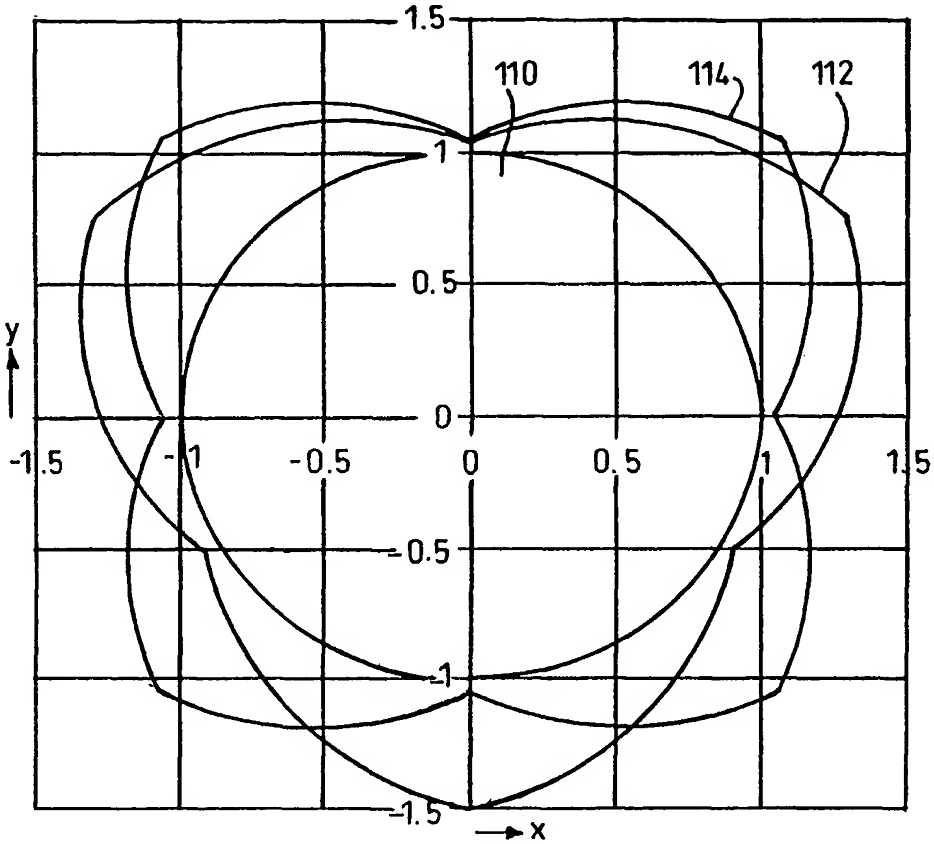


Fig.17.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114
112
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0.5
y
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Fig.18.

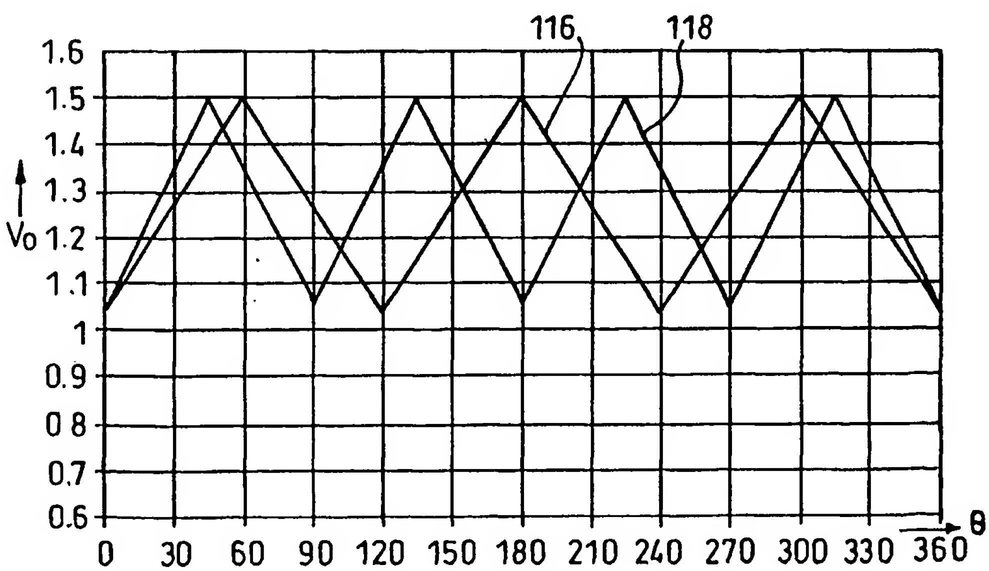
116
118
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Fig.19.

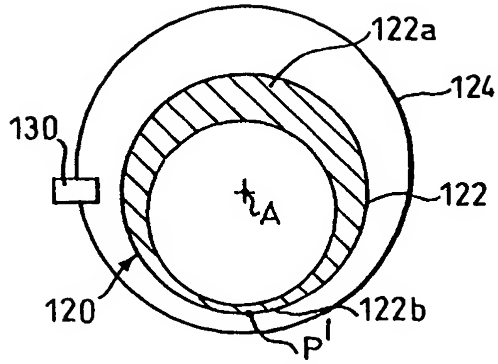

Fig.20.

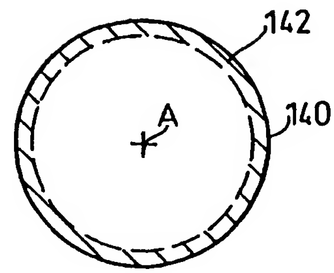

Fig.21.

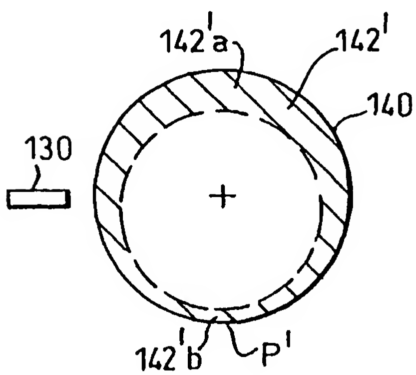

Fig.22.

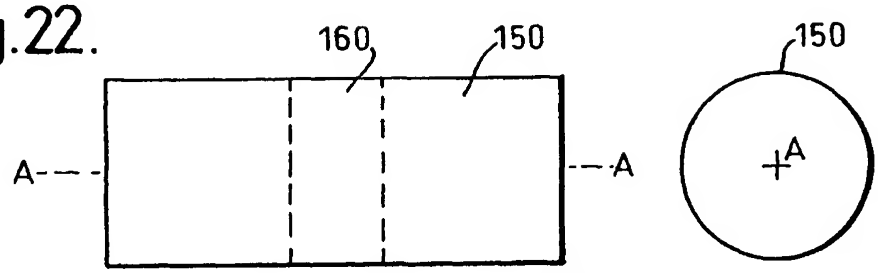

Fig.23a.

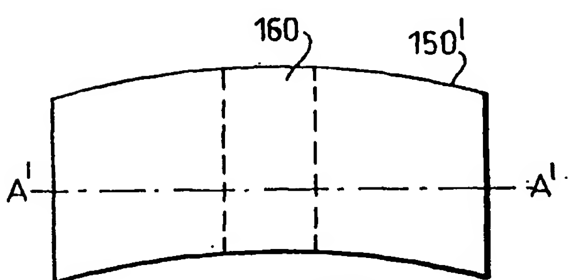

Fig.23b.

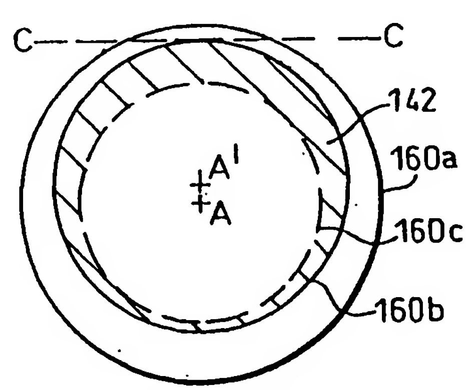

Fig.23c.